The Los Alamos spheromak programme

Article *in* Nuclear Fusion · January 2011

DOI: 10.1088/0029-5515/25/9/056

14 authors, including:

Rosalin Sherwood
Canterbury Christ Church University

George J Marklin
University of Washington

Rulon Linford
Lawrence Livermore National Laboratory

Thomas Jarboe
University of Washington

The Los Alamos spheromak programme

1985 Nucl. Fusion 25 1313

(http://iopscience.iop.org/0029-5515/25/9/056)

THE LOS ALAMOS SPHEROMAK PROGRAMME

B.L. WRIGHT, A.R. SHERWOOD, A.G. SGRO,
D.A. PLATTS, J. MARSHALL, G.J. MARKLIN,
R.K. LINFORD, S.O. KNOX, P.L. KLINGNER,
T.R. JARBOE, H.W. HOIDA, I. HENINS,
J.C. FERNÁNDEZ, C.W. BARNES
Los Alamos National Laboratory, Los Alamos,
New Mexico, United States of America

ABSTRACT. Experiments and theory at Los Alamos have contributed to advances and increased understanding of spheromak physics. Application of the relaxation principle and the concept of helicity injection has led to new, improved formation methods and to the ability to sustain spheromaks for long times against resistive decay. Use of oblate flux conservers has provided gross stabiltty of the spheromak, even in the presence of bias magnetic fields. Magnetic diagnostics have seen oscillations caused by rotating non-resonant internal kink modes. The stability thresholds of these modes agree with the measured equilibrium of the spheromak, confirming that those equilibria depart significantly from the minimum-energy state. Reduction of impurities and use of background filling gas have created resistively decaying spheromaks with non-radiation-dominated confinement.

1. FORMATION AND SUSTAINMENT

Compact toroid magnetic fusion concepts are those for which the confining magnetic fields are determined by currents flowing within the plasma itself and for which no material structures are required to link the torus. Concepts in this class, which includes spheromaks and field-reversed configurations, offer reactor advantages that result from the simplified geometries of the confinement chamber. In the case of the spheromak [1], the plasma currents are largely force-free ($\vec{j} \parallel \vec{B}$), the toroidal and poloidal fluxes are comparable, and the toroidal field is small at the separatrix or conducting boundary. The feature that most distinguishes the different experiments of the US spheromak programme is the method used to form the configuration. The technique used in the CTX experiment at Los Alamos originated in the earliest days of the fusion programme [2] and involves the use of a magnetized co-axial plasma source (Fig.1). Poloidal flux generated by a solenoid within the inner electrode is linked by the toroidal flux generated by a radial discharge between inner and outer electrodes. At sufficiently high source current, magnetic pressure drives the field-imbedded plasma into an oblate conducting vessel (called the flux conserver), where a spheromak configuration is established.

Work at Los Alamos and elsewhere [3, 4] confirmed the view that, in bounded geometries, spheromak plasmas tend to relax toward unique equilibrium states that minimize the total magnetic energy while conserving the total magnetic helicity [1, 5]. An immediate consequence of this principle is that spheromaks can readily be formed in a variety of ways. A recent example is a second spheromak experiment at Los Alamos in which a kink-unstable magnetized z-pinch replaces the co-axial source [6]. The relaxation principle also removes the need for fast formation techniques (that were originally used) and allows spheromaks to be sustained well beyond their normal resistive decay times by the continued injection of magnetic helicity. This development has led to a sequence of changes in the operating mode of CTX during which the capacitor bank voltage was reduced from 45 to 10 kV, and the source discharge time was increased from 0.01 to typically 1.0 ms. CTX spheromaks have been sustained for over 5 ms. Studies of the CTX magnetic helicity balance show that the efficiency of helicity transfer from the magnetized electrode to the spheromak plasma is effectively 100% when resistive dissipation is taken into account. Though the sustained mode of operation is of interest for the development of a steady-state spheromak, source operation over about 1 ms results in excessive impurity production which cools the plasma. Electrode improvement efforts are presently under way. Thus the major confinement studies have been performed by using the decaying phase during which the spheromak is isolated from the source.

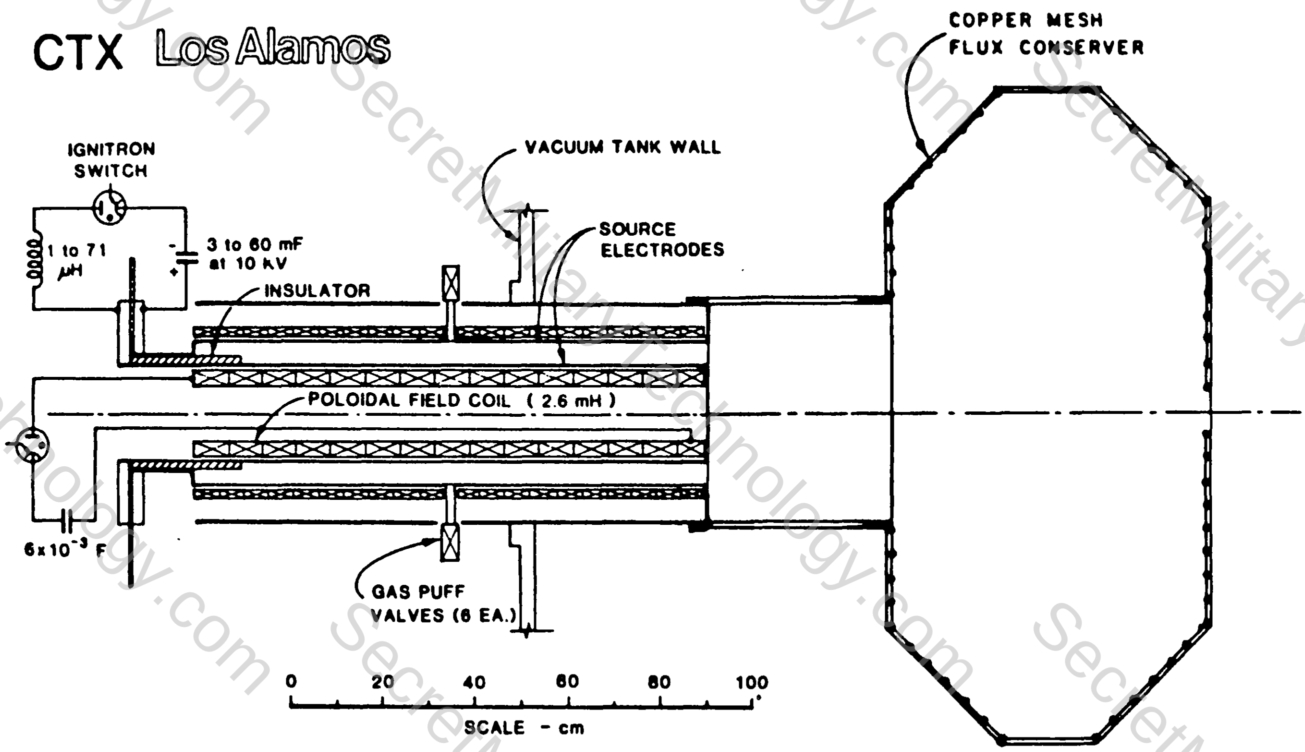

FIG.1. Scale drawing of magnetized co-axial plasma source and 0.67 m mesh flux conserver. Many different electrical circuits have been used, from simple LC circuits to multi-switch pulse-forming networks.

2. STABILITY

Since the time of its original inception, the gross stability of the spheromak has been a matter of concern [1, 7]. For containment by the image currents of a flux conserving shell as in CTX, only oblate geometries are expected to be stable to the internal tilt mode. Oblate flux conservers also provide limited stability against the tilting induced by an externally applied bias magnetic field. These expectations were verified in experiments with various solid-wall flux conserver geometries [8]. Mesh flux conservers made of discrete hoops and rods also provide gross MHD stability, and improved plasma conditions [9]. In recent work with a large oblate mesh flux conserver (Fig.1), stability has been observed for a bias flux up to 47 ± 7% of the spheromak poloidal flux. Indeed, application of a bias flux at the 5–15% level has led to increases in the lifetime of the freely decaying spheromak.

In the cleaner (non-radiation-dominated power balance) and hotter ($T_e \approx 100$ eV) CTX discharges, oscillations at low toroidal mode numbers ($n = 1, 2, 3$) are observed in the magnetic field of the configuration [10, 11]. Theoretical analysis has identified this behaviour with non-resonant internal kink modes that arise when the plasma current-density profile departs from the minimum-energy condition. Reconstruction of the mode patterns from perturbed currents measured in the mesh flux conserver agrees well with the theory, as do stability thresholds. The magnetic perturbations in CTX exhibit a rigid rotation that, for sustained spheromaks, appears due to a source-related $\vec{E} \times \vec{B}$ drift and, for decaying spheromaks, may result from electron diamagnetism. The observed oscillations saturate at small amplitudes and do not lead to disruption or relaxation back towards the "Taylor" minimum-energy equilibrium.

3. EQUILIBRIUM

The internal equilibrium currents can be inferred from measurements of the image currents in the copper wall of the flux conserver. The mesh construction of the flux conserver allows space- and time-resolved measurements of these image currents using Rogowski loop arrays. Using numerical modelling the internal equilibrium can be determined [11].

An equilibrium with force-free fields is given by $\nabla \times \vec{B} = \lambda\vec{B}$. The minimum-energy state has $\lambda \equiv \mu_0 j/B = \text{constant}$ [5]. The observed CTX equilibria differ from this 'Taylor' state by no more than 20% in energy per unit helicity [11]. They can be characterized by a non-constant $\lambda = \lambda(\Psi)$, where Ψ is the poloidal flux function. The image current data are accurately fit by a linear model $\lambda(\Psi) = \bar{\lambda}[1 + \alpha(2\Psi - 1)]$ with the parameter α adjusting the slope. During the spheromak sustainment by external helicity injection, α is about -0.3, with high current density driven by the source on the outer ($\Psi = 0$) flux surface. During the decaying phase the currents increasingly peak towards the magnetic axis ($\Psi = 1$), where the conductivity is highest. Thus α monotonically increases in time, passing through zero (Taylor state) but never returning.

4. CONFINEMENT

CTX energy losses were initially dominated by the effects of radiation from low-Z impurity charge states not in coronal equilibrium [12]. Improved vacuum practices, discharge cleaning, and optimized plasma formation operation reduced the impurities [10]. A static hydrogen background gas at 1–30 mT pressure filling the entire vacuum system before the discharge reduced the impurities generated in the plasma source. The neutral source was also required in the experiment to maintain the density ($n_e \approx (0.5-1.0) \times 10^{14}\ \text{cm}^{-3}$) for long lifetimes and prevent the sudden termination of the discharge associated with the density going to zero. Slower formation modes allowed higher magnetic fields ($\langle B^2\rangle_{vol}^{1/2} \approx 0.2-0.4$ T) and current densities ($j \approx (1-1.5)\ \text{MA}\cdot\text{m}^{-2}$).

CTX became the first spheromak to achieve electron temperatures of over 100 eV [9]. During the resistive decay of the spheromak in the 40 cm flux conserver the plasmas became collisionless ($\lambda_{mfp}/R > 1$) with a magnetic Reynolds number of $S > 10^4$. Ohmic heating to these temperatures was possible because of the 'pump-out' of the impurities by a rapid particle loss. The particle loss and the associated ionization and heating of the neutral particles required to maintain the density are the major energy loss processes in the decaying spheromak.

The electron temperature and density profiles obtained with a multi-point Thomson scattering diagnostic allow the calculation of volume-averaged pressure. Equilibrium models for the magnetic field structure are used to calculate values of peak local beta (15–25%) and volume-averaged beta (8–10%) [10]. The global magnetic energy decay time τ_{B^2} ($\tau_{B^2} \equiv \langle B^2\rangle / (\partial\langle B^2\rangle/\partial t)$ during decay) is consistent with the Spitzer-Härm resistivity [12], but with an anomaly factor that increases with j/n and the streaming parameter $v_{drift}/v_{thermal}$ on the magnetic axis. The global energy confinement time is calculated as $\tau_E = (3/2) \times \langle\beta\rangle_{vol}\tau_{B^2}$. The calculated τ_E increases with central temperature and density, with best values of $\tau_E > 40\ \mu s$ and $n\tau_E > 4 \times 10^9\ \text{s}\cdot\text{cm}^{-3}$. The CTX results have led to a reactor design for a steady-state spheromak with simple geometry, efficient plasma confinement, and high power density [13].

REFERENCES

[1] ROSENBLUTH, M.N., BUSSAC, M.N., Nucl. Fusion **19** (1979) 489.

[2] ALFVÉN, H., LINDBERG, L., MITLID, P., J. Nucl. Energy, Part C: Plasma Physics **1** (1960) 116.

[3] JARBOE, T.R., HENINS, I., SHERWOOD, A.R., BARNES, C.W., HOIDA, H.W., Phys. Rev. Lett. **51** (1983) 39.

[4] TURNER, W.C., GOLDENBAUM, G.C., GRANNEMAN, E.H.A., HAMMER, J.H., HARTMAN, C.W., PRONO, D.S., TASKA, J., Phys. Fluids **26** (1983) 1965.

[5] TAYLOR, J.B., Phys. Rev. Lett. **33** (1974) 1139.

[6] JARBOE, T.R., BARNES, C.W., PLATTS, D.A., WRIGHT, B.L., Comments Plasma Phys. Controll. Fus. **9** 4 (1985).

[7] JARBOE, T.R., HENINS, I., HOIDA, H.W., LINFORD, R.K., MARSHALL, J., PLATTS, D.A., SHERWOOD, A.R., Phys. Rev. Lett. **45** (1980) 1264.

[8] ARMSTRONG, W.T., BARNES, D.C., BARTSCH, R.R., COMMISSO, R.J., EKDAHL, C.A., et al., in Plasma Physics and Controlled Nuclear Fusion Research 1980 (Proc. 8th Int. Conf. Brussels, 1980), Vol.1, IAEA, Vienna (1981) 481.

[9] JARBOE, T.R., BARNES, C.W., HENINS, I., HOIDA, H.W., KNOX, S.O., et al., Phys. Fluids **27** (1984) 13.

[10] BARNES, C.W., JARBOE, T.R., HENINS, I., SHERWOOD, A.R., KNOX, S.O., et al., Nucl. Fusion **24** (1984) 267.

[11] KNOX, S.O., BARNES, C.W., MARKLIN, G.J., JARBOE, T.R., HENINS, I., et al., Observations of Spheromak Equilibria which Differ from the Minimum Energy State and have Internal Kink Distortions, submitted to Phys. Rev. Lett., 1985, and in Proceedings of the Seventh CT Symposium, Santa Fe, NM (1985).

[12] BARNES, C.W., JARBOE, T.R., HOIDA, H.W., WRIGHT, B.L., HULSE, R.A., POST, D.E., Zero-Dimensional Energy Balance Modeling of the CTX Spheromak Experiment, Rep. LA-UR-84-3667 (to be published in Nucl. Fusion).

[13] KRAKOWSKI, R.A., HAGENSON, R.L., Steady-State Spheromak Reactor Studies, Rep. LA-UR-85-513 (1985).